FERMILAB-Proposal-0571

A Proposal to Search for Integer Charged Quarks

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Abstract

We propose to use the CØ Large Angle Recoil Spectrometer and the Warm jet target to do a sensitive search for light, stable particles of integer charge. Sensitivities of $\lesssim 10^{-6}$ of kaon production are expected over the entire mass region from slightly above the pion mass up to about the deuteron mass with the exception of small gaps at the kaon and proton masses.

18 pgs

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I Introduction

The quark model has had remarkable phenomenological success describing properties of hadronic matter in terms of a substructure of point-like constituents. The original model, as proposed by Gell-mann[1] and Zweig[2] postulated constituents with fractional charge. A later version by Han and Nambu[3] obtained similar results (while fixing a problem with statistics) using constituents of integer charge. Both the fractional charge (plus color) and the Han-Nambu scheme give adequate descriptions of the existing evidence for quark-like substructure; the preference for one model over the other being largely a matter of taste.

An intriguing feature of the quark model is the indication that quarks are relatively light. The early onset of Bj scaling indicates that the "effective" masses of the quarks inside the proton are less than 500-600 MeV/c^2. The stability of the proton indicates quark masses greater than one third the proton mass. One is thus led, we think quite naturally, to expect the quark mass to be near that of the K meson (m_{K^+} = 494 MeV/c^2).

Searches for fractionally charged particles tend to be insensitive to mass, and limits on their production or existence in nature, are impressively low. This is, for the most part, due to the striking experimental signal a fractionally charged particle would have. For example, the super momentum search of Nash et al[4] sets an upper limit for the production of $q = -\frac{1}{3}$ e quarks at about 10^{-38} cm^2 for all masses up to 8.5 GeV/c^2. It is these low limits (and not those on integer charge quark production) that have led to the conjecture that quarks are permanently confined in the proton and never exist in the free state.

The evidence against the existence of quarks of integer charge is not nearly as compelling. A recent experiment by Alvarez and coworkers[5] searched for stable integer charged quarks by looking for naturally occurring "hydrogen" molecules with an anomalous charge to mass ratio. The sensitivity of the experiment for quarks of mass greater than 2 GeV/c^2 was quite impressive, i.e., 1 part in 10^{18}, however, at lower masses it was quite a bit poorer, typically 1 part in 10^{14} or worse. Searches for the production of integer charged quarks have very similar results, i.e., good sensitivity for $m \gtrsim 2$ GeV/c^2 and poorer or no sensitivity at lower masses[6]. In the vicinity of the K meson mass there are only a few reported limits. One measurement, an AGS experiment by Lobkowicz et al[7], primarily designed to measure the lifetime ratio of K^+ and K^- mesons, report that a stable particle component of their kaon beam would have to be below a level of 1 part in 300 of the Kaon flux. They were sensitive to a narrow mass region of about $\pm$ 50 MeV/c^2 around the Kaon mass. Other experiments, typically beam surveys, report similar results, usually a sensitivity of roughly 1 part in 100 or so over limited regions of the mass spectrum.

More or less typical of these results are those reported by Denisov at the Dubna Instrumentation Conference in 1970[8]. In his talk on Serpuhkov Cherenkov counters he displayed results on beam surveys using a variety of Cherenkov counters. A pressure curve for a 45 GeV/c beam is shown in Fig. 1a. A mass scale has been added. No signal greater than about 1 part in 100 of the kaon yield is apparent for masses from about 220 to 460 MeV/c^2. A second pressure curve (with pions vetoed in a threshold counter, is shown in Fig. 1b, again with a mass scale added. Here the rejection appears to be somewhat better, as good as 1 part in 10^4, but only over a rather limited mass region, 600 MeV/$c^2 \lesssim m \lesssim 900$ MeV/c^2, and here only 5 points are measured. Measurements of this type have been done at all particle accelerators with similar results[9]. However, as far as we can tell, there has never been an experiment specifically designed to search for the production of unusual integer charged particles with low masses; this is, however, just the region where one might naturally expect to find Han-Nambu type quarks if they existed.

We propose to do a careful search for stable, integer charge particles in the mass range between the pion and deuteron masses. We expect to have a sensitivity for production of better than 1 part in 10^6 of the kaon yield over the entire mass range with the exception of small gaps of $\sim \pm$ 20 MeV/c^2 around the kaon and proton masses, where the sensitivity will be somewhat poorer.

The CØ Large Angle Recoil Spectrometer is an ideal device for this search. It couples the high energies available at the Fermilab accelerator with good acceptance and resolution for low momentum secondaries. High incident energy may be very important despite the low mass range covered. Recall that the direct production of light (point-like) electrons is roughly 10^{-4} that of pions at Fermilab energies[10] while at Los Alamos, which is well above electron production threshold, the direct electron production is substantially smaller[11]; $\lesssim 3 \times 10^{-6}$ of the pion yield. The low momentum and high resolution of the Large Angle Recoil Spectrometer is also important. At low momentum, high mass resolution is obtainable by time of flight techniques coupled with good momentum resolution. Also at low momentum charged kaons decay away profusely, reducing their contribution to background.

In light of the extreme ramifications the discovery of a particle of this type would have, and also the importance of establishing a meaningful upper limit on their production, a sensitive search is clearly warranted.

II Technique

We propose to use the CØ Large Angle Recoil Spectrometer with minor modifications to improve its time of flight measuring capabilities. By measuring both the momentum p and velocity v of particles produced in the internal target we can determine their mass according to the relation

$$m = p\sqrt{1/v^2 - 1/c^2}$$

Expressing time of flight in nanoseconds and the flight path d in feet gives (to good accuracy)

$$m = p\sqrt{t^2/d^2 - 1}.$$

Thus the mass resolution can be expressed in terms of the momentum and time of flight resolution as

$$\delta m = \left[\left(\frac{\partial m}{\partial p}\right)^2 \delta p^2 + \left(\frac{\partial m}{\partial t}\right)^2 \delta t^2\right]^{1/2}$$

$$= \left[m^2\left(\frac{\delta p}{p}\right)^2 + \frac{p^2}{d^2}\left(\frac{p^2}{m^2} + 1\right) \delta t^2\right]^{1/2}$$

For the CØ Spectrometer, $\delta p/p \simeq .003/p$ (p in GeV/c) and d can be as large as 50 feet. Coupling this with the typical "best" time of flight resolution of 0.25 nanoseconds (σ), we get the resolution curve (at the kaon mass) shown as a function of secondary momentum in Fig. 2. The rise at very small momentum, where the effect of time of flight errors are small, is due to the increasing uncertainty in the momentum. The rise at large momentum where the momentum measurement is good, is due to the onset of relativistic effects which makes the time of flight measurements less effective. The optimum momentum appears to be between 0.4 and 0.5 GeV/c, where $\delta m \simeq 4.5$ MeV/c^2. If the mass resolution were purely Gaussian, a σ of 4.5 MeV/c^2 would mean a rejection of kaon backgrounds of 5 parts in 10^5 for masses more than 20 MeV/c^2 away from the kaon mass. At a secondary momentum of 400 MeV/c, 98% of the produced kaons decay more than 3 meters before the rear MWPC's of the spectrometer and fail to reconstruct as good events. Thus in an ideal situation we could expect a rejection against kaons of 1 part in 10^6 in a mass region which comes very close (20 to 25 MeV/c^2) to the kaon mass.

III Backgrounds

A number of effects could cause backgrounds at or above this level. Among them are:

i) Non Gaussian errors in the momentum measurement.

ii) Non Gaussian errors in the time of flight as determined in the photomultiplier-scintillator system.

iii) Accidental backgrounds

iv) Forward secondaries from kaon decays in flight.

We discuss each item separately.

i) Non Gaussian Errors in the Momentum Determination

At low momentum, the dominant contribution to the momentum uncertainty is multiple scattering in the two MWPC's around the bending magnet (see Fig. 4). The multiple scattering distribution has non-Gaussian tails from plural scattering which could yield corresponding non Gaussian effects in the mass determination.

The momentum measurement is sufficiently overconstrained in the spectrometer enabling us to identify those events where anomalously large momentum errors are made. These events can be eliminated from the sample.

ii) Non Gaussian Errors in the Time of Flight

The time of flight is correlated to the pulse height in the counters which in turn have Landau tails that are notoriously non-Gaussian. We plan to reduce this effect by doing time of flight between redundant sets of counters and requiring each combination to agree.

iii) Accidental Backgrounds

In Fig. 3 we show a time of flight distribution for 60K protons, which was accumulated in Experiment 198. While the time of flight resolution here is relatively poor ($\sigma \sim .8$ nsec), it is clear that at more than 4 σ from the proton peak there are no counts. showing how clean the spectrometer is. The good spatial resolution enables us to make tight cuts on the intersection at the midplane of the magnet and also in identifying the target position.

The counting rates in the rear detectors are quite low since they are at wide angles to the incident beam and well shielded. The front and rear MWPC's (time resolution ~100 nsec) are backed up with scintillation hodoscopes which help sort out multiple hit events. We thus have no doubt that the accidental level will be at least as good, and probably better than that obtained in Expt. 198.

iv) Forward Secondaries from K Decays

If a Kaon with the proper momentum to get through the spectrometer (~ .4 GeV/c, $\beta = .63$) decays to a muon in the dead forward direction, it would also have the proper momentum to get through the spectrometer yet the muons β would be close to 1. This could give a background which ranges continuously downward from the Kaon time of flight, obscuring a quark signal if it exists.

Of the 98% of the Kaons which decay before 3 meters in front of the rear MWPC's, 90% decay before the time of flight measurement is started. Of those decays which occur over the time of flight path only those which have a decay product in the forward direction which is within $\lesssim 1°$ of the Kaon direction will pass all of the reconstruction tests. These correspond to about 3×10^{-5} of the K decays. Thus for those K's which decay "early" there should be no problem. The final time of flight measurement will be made in each of 3 planes of 1/2" thick scintillator. Although these planes are rather large (36" × 10") a 20% dE/dx measurement in each plane is readily achievable. Remember we are comparing a dE/dx for masses near the Kaon mass to one at the muon mass. At these momenta, dE/dx is a strong function of mass, Kaons have almost twice that of muons. Thus a 20% measurement (repeated 3 times) will more than suffice to identify those events where a K decayed into a light secondary, which in turn triggered the rear time of flight counters. Thus we believe that with care, we can achieve a sensitivity of 1 part in 10^6 of the Kaon yield over almost the entire mass range from somewhat above the pion mass to about the deuteron mass.

IV Experimental Details

A) Spectrometer Configuration

We plan to configure the spectrometer as shown in Fig. 4, positioning the spectrometer arm at $\sim 43°$ with respect to the incident proton beam. At this angle, the rear arm of the spectrometer points at the far corner of the room. This maximizes the time of flight path. Since the momentum measurement is dominated by multiple scattering, it is not necessary to extend it to the back of the room. At the rear corner, three planes of 36" × 10" × 1/2" counters, each viewed by two phototubes will be used to determine time of flight and dE/dx. At both the existing front and rear MWPC's, two 1/2" thick counters will be introduced which will also measure time of flight and dE/dx. These 7 counter planes together with a machine synchronous r.f. signal will provide the redundant time and ionization information discussed in the previous section.

The modification of the spectrometer thus consists of merely adding seven counters in places which are easily accessible, and two planes of MWPC's in front of the final timing counters for determination of the position of the trajectory at that point. The Indiana University Polarimeter used in Expt. 313 can easily be detached and placed to the side.

B) Rates

An approximate formula for low $p_\perp$ pion production is[12] (x = radial x $= 2P^*/\sqrt{s}$)

$$\frac{d\sigma}{dx\,dp_\perp} = 1.8 \times 10^{-23}\ p_\perp\ e^{-6p_\perp}\ (1-x)^4\ \mathrm{cm}^2/\mathrm{GeV}/c$$

The x and $p_\perp$ acceptance of the spectrometer is $\Delta x = .01$ (at $x = -.4$) and $\Delta p_\perp = .03$ GeV/c (at $p_\perp = .3$ GeV/c). The number of pions into the spectrometer acceptance per second is the product of this cross section and acceptance with the instantaneous beam rate (2×10^{13} particles/pulse $\times 5 \times 10^4$ circulation/sec), the density of the jet target ($\sim 10^{-7}$ gms/cm^2) Avogadros number (6×10^{23} protons/gm), and the phi bite ($.1/2\pi$)

$$N = 5\times10^4\times2\times10^3\times10^{-7}\times6\times10^{23}\times1.8\times10^{-23}\times.3\times e^{-1.8}(.6)^4\times.01\times.03\times.1/2\pi$$
$$= 3\times10^4\ \pi\text{'s/sec.}$$

Kaons, at the target are about 1 tenth of this. So with 360 ramps/hour and one second of jet per ramp we will have 10^6 K's produced at the target/hour.

The data system could not handle all of these particles so pions will be deliberately timed out. A small number will be prescaled into the trigger to provide a time reference. Kaons will trigger the system but will be reduced to manageable rates because of decays in flight. When running with positive secondaries, protons will also have to be prescaled to reduce the data rate.

C) Requested Running Time

We would like to run until our sensitivity is limited by backgrounds. Right now we are confident that over most of the mass range these backgrounds will be less than 10^{-6} of the Kaon yield; this level should be achieved in a few hours. The ultimate sensitivity can only be determined after a detailed analysis. It thus would seem that 100 hours of running with negatives and another 100 hours of running with positives would be a reasonable program. Emphasis will be placed on negatives since because of the lower K^- yield relative to K^+'s and $\bar{p}$'s relative to p's we expect things to be cleaner. The running would be split between a number of momenta to provide some handles on systematic effects. Tuning and background measurements would require another 100 hours. Thus a total of 300 hours would be adequate for the proposed measurements.

D) Equipment

The experiment will require the Large Angle Recoil Spectrometer and Warm jet target currently installed at CØ. The prep equipment currently in use would be used together with the Rutgers PDP11 computer. Additional equipment would be small. Seven timing counters and the additional MWPC planes will be provided by the experimenters and we'll require a few (one or two) CAMAC ADC's and TDC's from PREP. Fermilab would be expected to provide liquid helium for the magnets. The bulk of the data analysis can be performed on the Rutger's 11.

E) Manpower

Since only minor modifications to an existing working apparatus are required we believe the listed proponents can implement and run this experiment without substantially interfering with our other efforts, primarily the analysis of Expt 198 and the implementation of Expt 552.

F) Time Scale

We think that the topical interest warrants that this experiment be soon. The extra equipment is being prepared now and we will be ready to run by late Fall of 1977.

V. Remarks

This experiment will correct what appears to be a glaring oversight in the experimental search for quarks. The proposed search is optimized for low mass, integer charged, stable quarks, objects which have been hypothesized but apparently never searched for with great care.

In the event of a discovery, we will start on a complete program of measuring their properties, such as their total cross section, lifetime etc. The CØ spectrometer will be adequate for at least crude, first round, measurements of this type.

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Figure Captions

Figure 1 a) Pressure curve for a 45 GeV/c beam at Sepukhov with a mass scale added, from ref. 8.

b) Similar results for a different Cherenkov system in a 40 GeV/c beam. This curve was also taken from ref. 8.

Figure 2 The expected mass resolution (σ) as a function of secondary momentum, for the Large Angle Recoil Spectrometer configured as described in the proposal.

Figure 3 A time of flight distribution for .9 GeV/c protons measured in experiment 198. The curve is reasonably close to a Gaussian with a σ of .8 nanosecs. The points lying on horizontal axis are actually zero.

Figure 4 The proposed experimental configuration showing the deployment of counters, MWPC's and Hodoscopes.

45 GeV/c

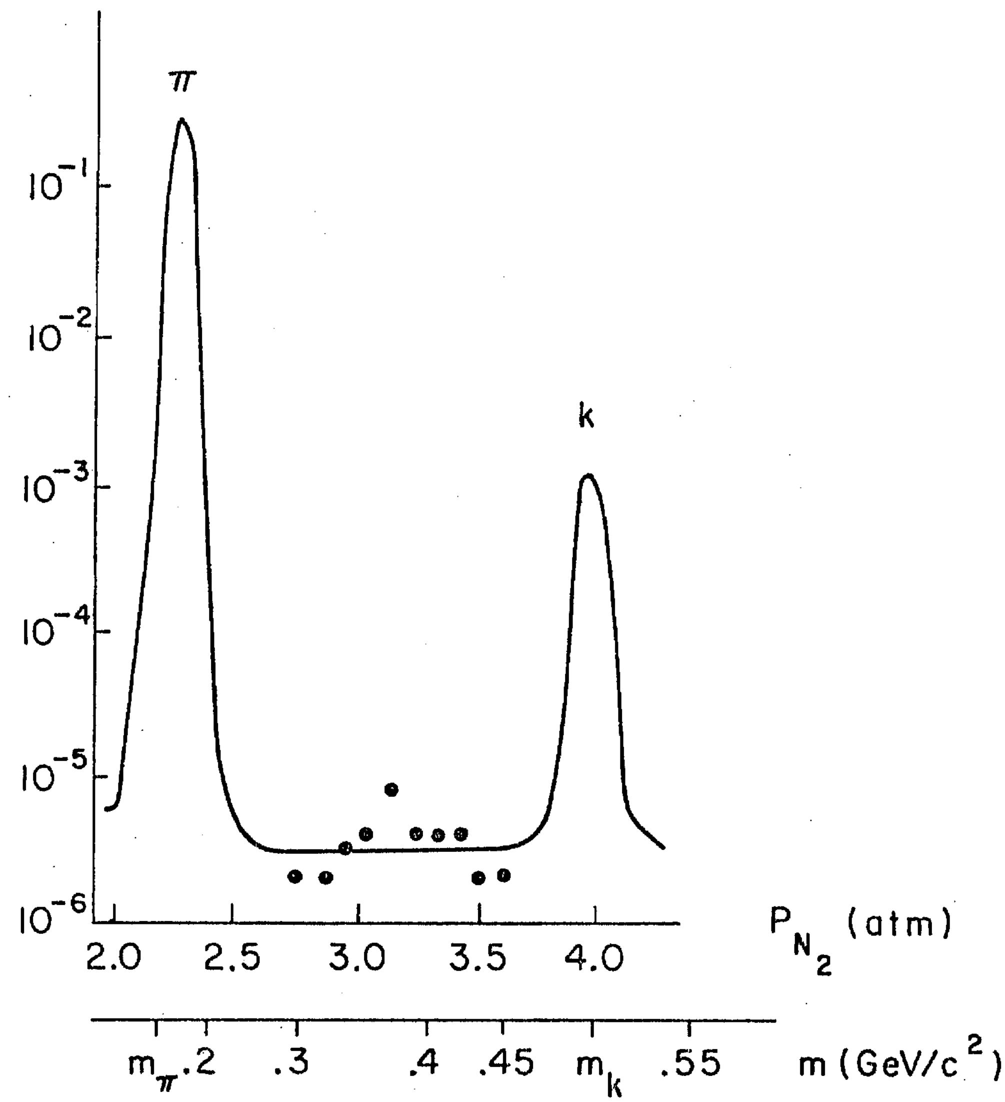
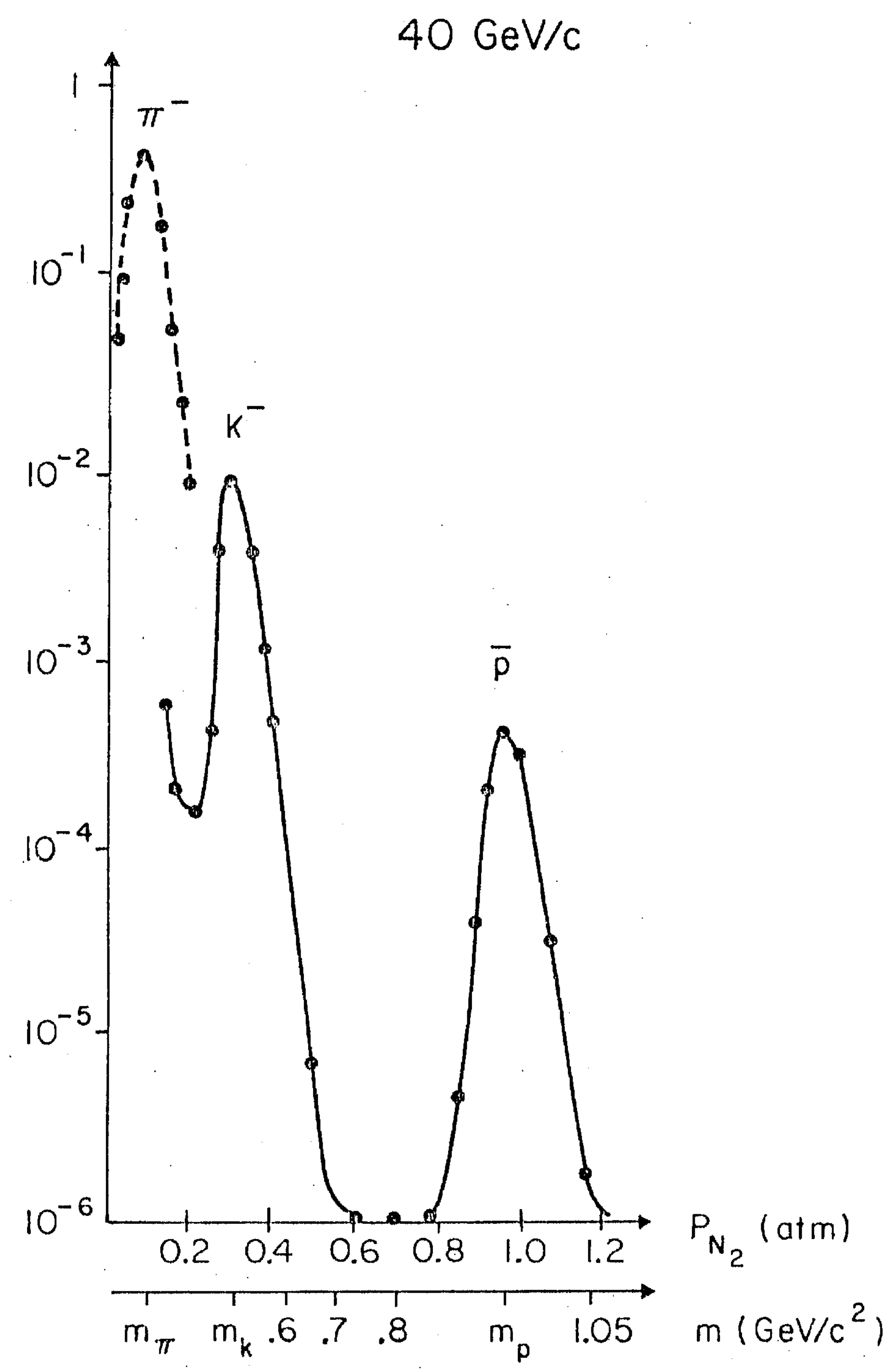
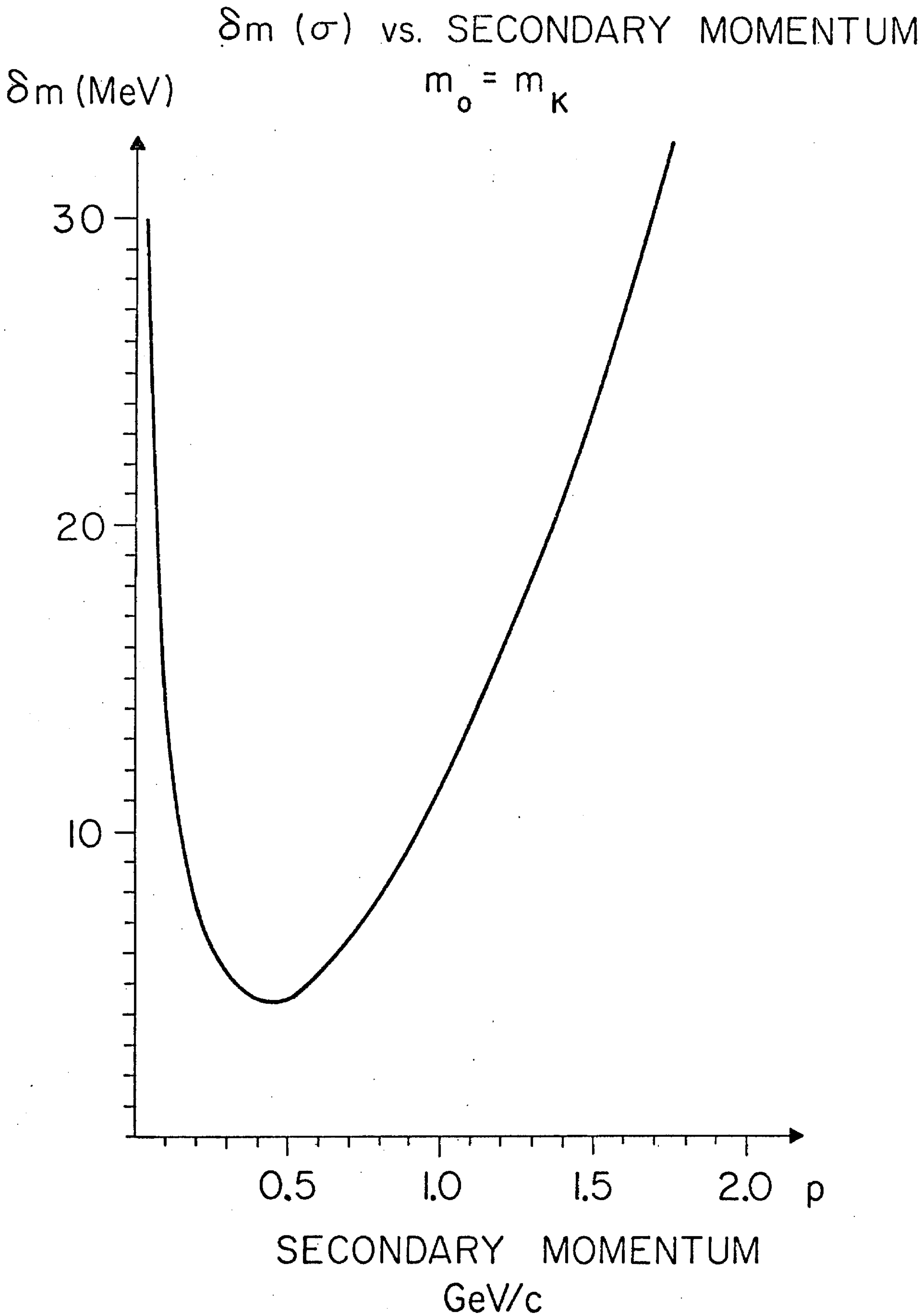


Figure 1a



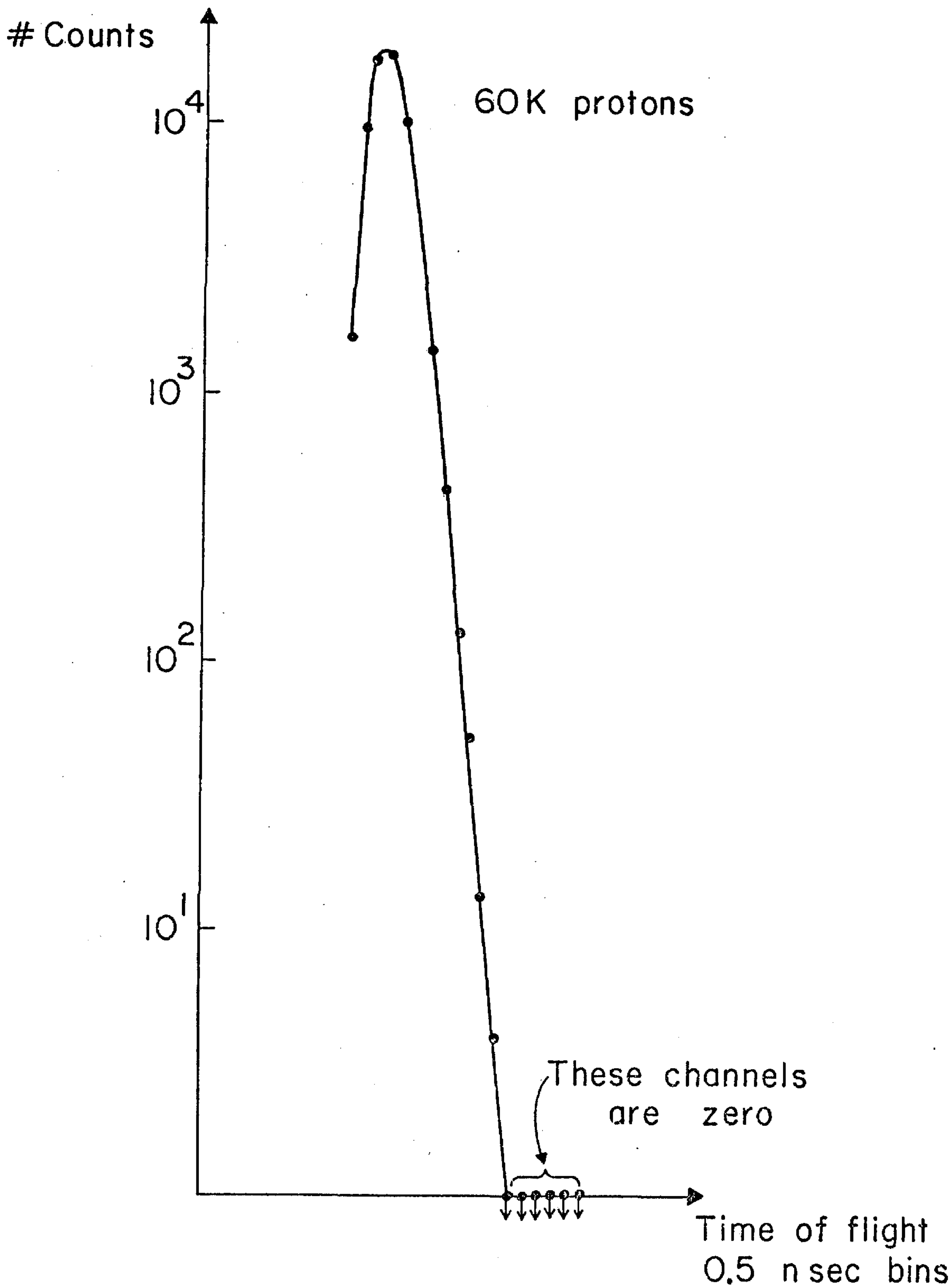
40 GeV/c
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
π^-
K^-
$\bar{p}$
0.2
0.4
0.6
0.8
1.0
1.2
P_{N_2} (atm)
m_π
m_k
.6
.7
.8
m_p
1.05
m (GeV/c^2)

Figure 1b



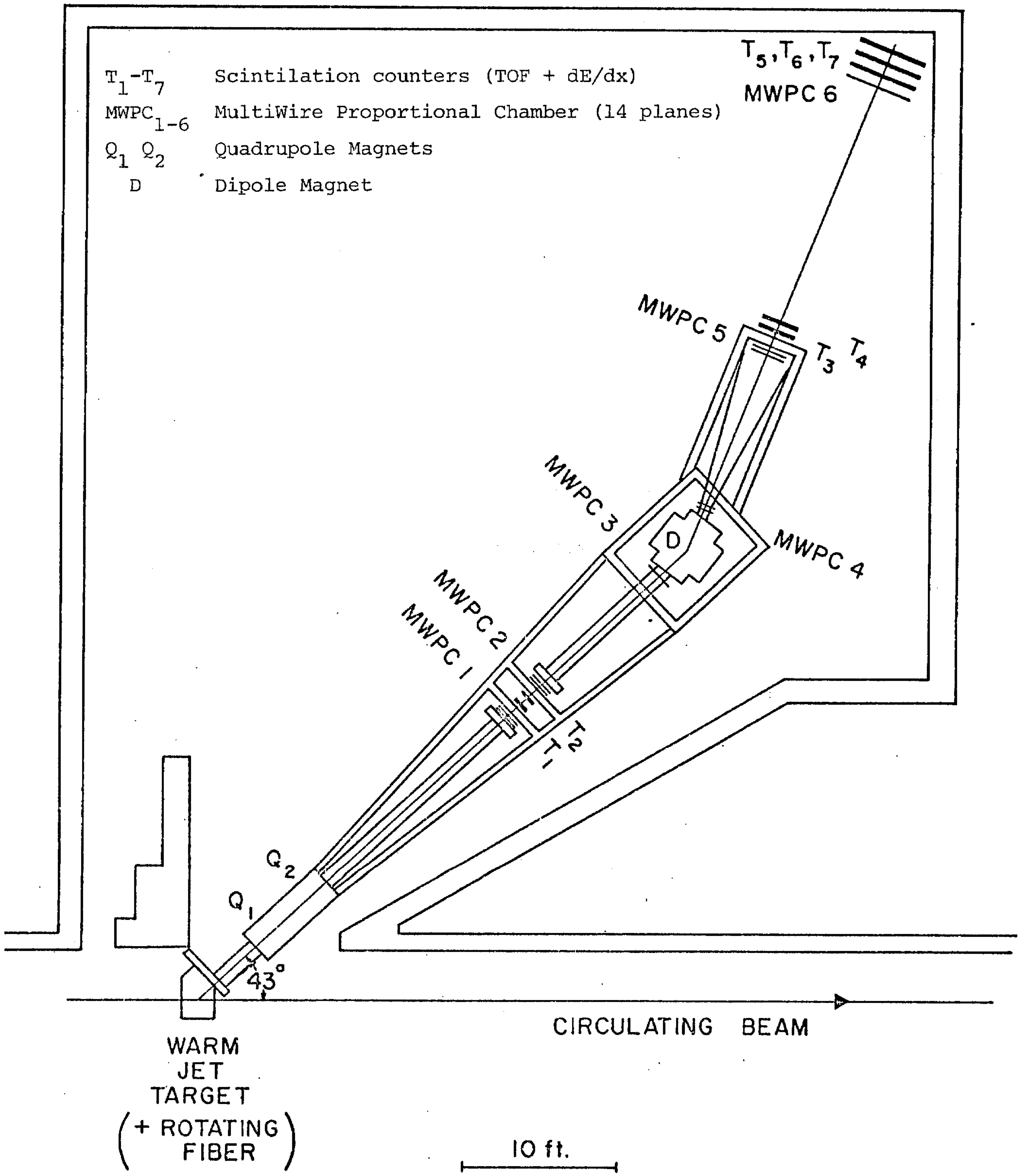
δm (σ) vs. SECONDARY MOMENTUM
δm (MeV)
m₀ = m_K
30
20
10
0.5
1.0
1.5
2.0
p
SECONDARY MOMENTUM
GeV/c

Figure 2



Counts
60K protons
10^4
10^3
10^2
10^1
These channels
are zero
Time of flight
0.5 n sec bins

Figure 3



T_1-T_7 Scintilation counters (TOF + dE/dx)
$MWPC_{1-6}$ MultiWire Proportional Chamber (14 planes)
Q_1 Q_2 Quadrupole Magnets
D Dipole Magnet
T_5, T_6, T_7
MWPC 6
MWPC 5
T_3 T_4
MWPC 3
D
MWPC 4
MWPC 2
MWPC 1
T_2
T_1
Q_2
Q_1
43°
CIRCULATING BEAM
WARM JET TARGET (+ ROTATING FIBER)
10 ft.

Figure 4